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U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

ATTORNEY'S DOCKET NUMBER  
P/61757-PCT

**TRANSMITTAL LETTER TO THE UNITED STATES  
DESIGNATED/ELECTED OFFICE (DO/EO/US)  
CONCERNING A FILING UNDER 35 U.S.C. 371**

U.S. APPLICATION NO. (if known, see 37 CFR 1.5)  
**10/019141**

INTERNATIONAL APPLICATION NO.  
**PCT/GB00/02418**

INTERNATIONAL FILING DATE  
**June 22, 2000**

PRIORITY DATE CLAIMED  
**June 23, 1999**

TITLE OF INVENTION **PIEZO-ELECTRIC TRANSFORMER CIRCUIT**

APPLICANT(S) FOR DO/EO/US **Anthony John SALLOWAY, Caroline Elizabeth MILLAR**

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371 (f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. ☐ The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
  - a. ☐ is attached hereto (required only if not communicated by the International Bureau).
  - b. ☒ has been communicated by the International Bureau.
  - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
  - a. ☐ is attached hereto.
  - b. ☐ has been previously submitted under 35 U.S.C. 154(d)(4).
7. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3)).
  - a. ☐ are attached hereto (required only if not communicated by the International Bureau).
  - b. ☐ have been communicated by the International Bureau.
  - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
  - d. ☐ have not been made and will not be made.
8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☐ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

**Items 11 to 20 below concern document(s) or information included:**

11. ☐ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A **FIRST** preliminary amendment.
14. ☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
15. ☐ A substitute specification.
16. ☐ A change of power of attorney and/or address letter.
17. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
18. ☐ A second copy of the published international application under 35 U.S.C. 154(d)(4).
19. ☐ A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
20. ☒ Other items or information: Receipt Acknowledgment Postcard

531 Rec'd PCT/ 20 DEC 2001

U.S. APPLICATION NO. <b>10/019141</b>		INTERNATIONAL APPLICATION NO. <b>PCT/GB00/02418</b>		ATTORNEY'S DOCKET NUMBER <b>P/61757-PCT</b>	
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21. <input checked="" type="checkbox"/> The following fees are submitted: <b>BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :</b> Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO ..... \$1,040.00  International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO ..... \$890.00  International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... \$740.00  International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) ..... \$710.00  International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) ..... \$100.00  <b>ENTER APPROPRIATE BASIC FEE AMOUNT =</b>				<b>CALCULATIONS PTO USE ONLY</b>          	
				\$890.00	
Surcharge of <b>\$130.00</b> for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).				\$0.00	
CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE	\$	
Total claims	33 - 20 =	13	x \$18.00	\$234.00	
Independent claims	5 - 3 =	2	x \$84.00	\$168.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ \$280.00	\$0.00	
<b>TOTAL OF ABOVE CALCULATIONS =</b>				\$1,292.00	
<input type="checkbox"/> Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.				\$0.00	
<b>SUBTOTAL =</b>				\$1,292.00	
Processing fee of <b>\$130.00</b> for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				\$0.00	
<b>TOTAL NATIONAL FEE =</b>				\$1,292.00	
Fee for recording the enclosed assignment (37 CFR 1.21 (h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). <b>\$40.00</b> per property +				\$0.00	
<b>TOTAL FEES ENCLOSED =</b>				\$1,292.00	
				Amount to be refunded:	\$
				charged:	\$

a. ☒ A check in the amount of **\$1,292.00** to cover the above fees is enclosed.

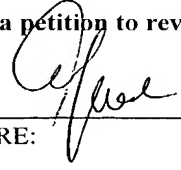
b. ☐ Please charge my Deposit Account No. \_\_\_\_\_ in the amount of \$\_\_\_\_\_ to cover the above fees.  
A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any  
overpayment to Deposit Account No. 11-1145. A duplicate copy of this sheet is enclosed.

**NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.**

**SEND ALL CORRESPONDENCE TO:**

**KIRSCHSTEIN, OTTINGER, ISRAEL & SCHIFFMILLER, P.C.**  
 489 Fifth Avenue  
 New York, New York 10017  
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REGISTRATION NUMBER 27,564

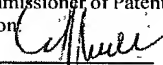
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**PATENTS**  
**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

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(date)   
Alan Isrjeh  
Reg. No. 27,564

International Application No.: PCT/GB00/02418  
International Filing Date : June 22, 2000  
In re: Application of : Anthony John SALLOWAY, et al.  
Deposited : December 20, 2001  
For : PIEZO-ELECTRIC TRANSFORMER CIRCUIT

New York, New York  
December 20, 2001

**PRELIMINARY AMENDMENT**

BOX: PCT  
Commissioner of Patents and Trademarks  
Washington, D.C. 20231

Sir:

Prior to calculation of the filing fee and before examination, kindly amend the above  
captioned application as follows:

**IN THE CLAIMS:**

Please cancel claims 1-33, without prejudice.

Please add the new set of claims set forth on the enclosed pages.

**IN THE ABSTRACT:**

Delete the "Abstract" on the PCT cover sheet and replace it with the "Abstract of the Disclosure" set forth on a separate sheet attached hereto.

**REMARKS**

An abstract has been provided on a separate sheet; and the claims have been amended to conform to U.S. practice.

Wherefore, an early action on the merits is earnestly solicited.

Respectfully submitted,

KIRSCHSTEIN, OTTINGER, ISRAEL & SCHIFFMILLER, P.C.

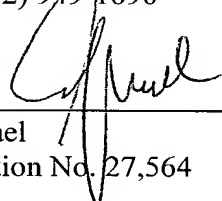
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### **ABSTRACT OF THE DISCLOSURE**

A piezo-electric transformer circuit incorporates a piezo-electric transformer comprising a multi-element primary region and a single element secondary region mutually joined together. In operation, the circuit applies a drive signal to the primary region to excite the primary and secondary regions into longitudinal resonance, thereby generating a high potential signal at the secondary region. The drive signal is derived from the signal at the secondary region in a self-oscillating feedback loop configuration. The transformer is fabricated from a hard piezo-electric ceramic material having a dielectric loss of substantially 0.005 or less at 1 kHz. Although such a hard ceramic does not provide as high a charge coefficient as softer piezo-electric ceramic materials, it is found that hard ceramics provide surprisingly improved energy conversion when used in piezo-electric transformer power supplies.

**PROPOSED NEW CLAIMS**

34. A piezo-electric transformer circuit, comprising: a piezo-electric transformer having mutually vibrationally coupled primary and secondary regions, the secondary region being operable to provide an output signal for use in generating an output from the circuit; and vibration exciting means for exciting the transformer into vibration to generate the output signal, the transformer including a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz frequency.

35. The circuit according to claim 34, wherein the exciting means is operable for exciting vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions.

36. The circuit according to claim 34, wherein the exciting means incorporates a network operable for phase shifting and amplifying the output signal to generate a drive signal for exciting and thereby sustaining vibrations within the transformer.

37. The circuit according to claim 36, wherein the network is operable for phase shifting the output signal in a range of 30° to 150° to generate the drive signal.

38. The circuit according to claim 36, wherein the network is operable for phase shifting the output signal in a range of 30° to 90° to generate the drive signal.

39. The circuit according to claim 34, wherein the exciting means incorporates amplifiers arranged in a bridge configuration operable for driving the transformer.

40. The circuit according to claim 34, wherein the exciting means is operable for exciting vibrations and incorporates at least one inductor through which the transformer is driven

at its primary region, the inductor being operable for electrically resonating with a capacitor provided by the primary region at a frequency corresponding to that of the vibrations.

41. The circuit according to claim 40, wherein said at least one inductor incorporates a ferrite core.

42. The circuit according to claim 34, and rectifying means for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in a form of a unipolar output potential.

43. The circuit according to claim 42, wherein the rectifying means incorporates a rectifier diode operable for providing a conductive path for the output signal to a ground potential to assist with developing the unipolar output potential.

44. The circuit according to claim 36, wherein the transformer is operable for imparting a greater voltage amplitude to the output signal relative to that of the drive signal.

45. The circuit according to claim 34, wherein the transformer is operable for vibrating in a longitudinal mode of acoustic resonance.

46. The circuit according to claim 34, wherein the primary region of the transformer comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited in parallel with other of the elements.

47. The circuit according to claim 46, wherein the transformer incorporates in a range of 2 to 40 elements in the primary region, and a single element in the secondary region.

48. A method of operating a piezo-electric transformer, the method comprising the steps of:





55. The method according to claim 53, and extracting signals from the secondary region of the transformer through an inductor arranged to electrically resonate with a capacitor provided by the secondary region at a frequency corresponding to that of the vibrations.

56. The method according to claim 48, and rectifying the output signal to provide a unipolar output potential from the transformer.

57. The method according to claim 56, wherein the rectifying step is performed by directing the output signal through a rectifier diode to a ground potential, the diode being operative to provide a conductive path to assist with developing the unipolar output potential.

58. The method according to claim 48, wherein the transformer is of elongate form operable to vibrate longitudinally along an elongate axis.

59. The method according to claim 48, wherein the transformer is operable to impart a greater voltage amplitude to the output signal relative to the drive signal.

60. The method according to claim 48, wherein the transformer is operable to vibrate in a longitudinal mode of mechanical resonance.

61. The method according to claim 48, and forming the primary region with a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the element.

62. The method according to claim 61, wherein the transformer incorporates in a range of 2 to 40 elements in the primary region, and a single element in the secondary region.

63. A personnel-wearable sensing apparatus operable for generating an elevated bias potential for use in the apparatus, the apparatus comprising a piezo-electric transformer circuit including a piezo-electric transformer having mutually vibrationally coupled primary and secondary

regions, the secondary region being operable to provide an output signal for use in generating an output from the circuit; and vibration exciting means for exciting the transformer into vibration to generate the output signal, the transformer including a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz frequency.

64. A piezo-electric transformer, comprising: mutually vibrationally coupled primary and secondary regions, the primary region incorporating a stack of piezo-electric material elements, each element incorporating electrical connections for connecting a drive signal thereto, the secondary region incorporating electrical connections for extracting an output signal therefrom, and the transformer comprising a piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz.

65. The transformer according to claim 64, wherein the transformer incorporates in a range of 2 to 40 elements in the primary region, and a single element in the secondary region.

66. A personnel-wearable sensing apparatus, comprising: a piezo-electric transformer operable for generating a bias potential for use in the apparatus, the transformer including mutually vibrationally coupled primary and secondary regions, the primary region incorporating a stack of piezo-electric material elements, each element incorporating electrical connections for connecting a drive signal thereto, the secondary region incorporating electrical connections for extracting an output signal therefrom, and the transformer comprising a piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz.

## PIEZO-ELECTRIC TRANSFORMER CIRCUIT

This invention relates to a piezo-electric transformer circuit and a method of operating the circuit.

5 Man-made piezo-electric materials such as lead zirconate titanate (PZT) are well known. The materials are often in the form of powders which can be sintered at elevated temperatures to form polycrystalline solids which can then be machined into components operable to couple between acoustic or vibrational radiation and corresponding electrical signals. The components can include, for example, ultrasonic transducers, microactuators and piezo-electric transformers.

10

Piezo-electric transformers are conventionally employed in power supply circuits providing high output potentials at low currents; in this context, high potential or high voltage means in the order of 100 volts to 10 kV, and low currents means in the order of tens of microamperes to milliamperes. Compared to circuits employing electro-magnetic devices for generating such high  
15 potentials, functionally equivalent circuits employing piezo-electric transformers are capable of being lighter-weight and more compact.

20

A conventional piezo-electric transformer circuit can incorporate a piezo-electric transformer comprising an elongate bar of PZT material comprising primary and secondary regions. In operation, an electrical drive signal is applied by the circuit to the primary region to excite vibrations therein which are coupled to the secondary region; the vibrations generate mechanical stresses in the secondary region and thereby high voltages therein, for example in the order of 1 kV. The high voltages are rectified to provide a high-voltage unipolar output from the circuit. The conventional transformer circuit suffers a problem that its efficiency deteriorates as its output is  
25 loaded; efficiency here is defined as a ratio of power delivered to a load connected to the output relative to input power provided to the circuit.

30

A United States patent no. 5 777 425 discloses a piezo-electric transformer comprising a rectangular plate of piezo-electric material. The transformer includes drive and pickup electrodes connected to a pulse generator for exciting the transformer at its mechanical resonance and thereby generating a high-voltage output. Applications for the transformer are disclosed in the patent,

namely in electronic copy machines, electrostatic air cleaners and for backlighting liquid crystal displays. The transformer is described as being fabricated from a known ceramic having a composition:

(a) Pb (Fe Nb) Zr Ti O<sub>3</sub>; or

5 (b) Pb (Mn Sb) Zr Ti O<sub>3</sub>; or

(c) Pb (Mn Nb) Zr TiO<sub>3</sub>; or

(d) Pb (Fe Sb) Zr TiO<sub>3</sub>.

Pb, Fe, Nb, Zr, Ti and O are chemical symbols corresponding to lead, iron, niobium, zirconium, titanium and oxygen respectively. Apart from disclosing the compositions, the patent does not  
10 indicate other properties required of the ceramics, for example their required mechanical Q-factor and charge coefficient.

In a published European patent application no. EP 0 730 338 A1, there is described a piezo-electric transformer for use in a low-power high-voltage power supply. The transformer is connected to  
15 an excitation circuit for driving the transformer at its resonance, and also connected to a diode rectification circuit for generating a unipolar high-voltage output potential. The transformer is described as optionally having a multilayer construction, layers of the transformer being mutually bonded by gluing, welding, brazing or similar. Piezo-electric materials suitable for fabricating the transformer are not disclosed in the published application.

20

In another published European patent application no. EP 0 665 600 A1, there is described a piezo-electric transformer and an associated electronic excitation circuit suitable for driving a high voltage discharge tube for backlighting liquid crystal displays. The application refers to a proprietary ceramic type HCEPC-28 made by Hitachi Metals Ltd. as being appropriate for  
25 fabricating the transformer. Moreover, the application refers to the transformer being of multilayer construction.

In the prior art, piezo-electric materials offering a relatively high piezo-electric coefficient are selected for high-power piezo-electric transformers; such relatively high piezo-electric coefficients  
30 are associated with relatively softer piezo-electric ceramics. Moreover, it is conventional practice

to design piezo-electric transformers to have associated operating resonant frequencies in the order of several tens of kHz.

5 The inventors have appreciated that it is not appropriate when designing high-power high-voltage power supplies incorporating piezo-electric transformers merely to select a piezo-electric transformer ceramic material purely on the basis of achieving a highest value of charge coefficient and mechanical resonance Q-factor to obtain maximum power supply conversion efficiency. Indeed, the inventors have appreciated to optimise the energy efficiency that piezo-electric ceramic dielectric loss is an important parameter which should be reduced to a relatively low level of  
10 substantially 0.005 or less at 1 kHz even at the expense of reducing charge coefficient.

According to a first aspect of the present invention, there is provided a piezo-electric transformer circuit incorporating a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the secondary region operable to provide an output signal for use  
15 in generating an output from the circuit, and vibration exciting means for exciting the transformer into vibration at its resonant frequency to generate the output signal, characterised in that the transformer comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz frequency.

20 The invention provides the advantage that the piezo-electric transformer is capable of being operated more efficiently, especially when the output from the circuit is more heavily loaded.

A test frequency of 1 kHz is accepted in the art as being a standard reference frequency for measuring piezo-electric material dielectric loss and is widely quoted in prior art literature.  
25 Moreover, the dielectric loss of a piezo-electric material is defined as the tangent of an electrical loss angle observed when electrically driving the material.

A hard piezo-electric ceramic material is defined as a piezo-electric ceramic material exhibiting a hardness corresponding to a Navy type I or III ceramic. Such a hard material is to be contrasted  
30 with a soft piezo-electric material which exhibits a hardness corresponding to a Navy type II

ceramic. Further definitions mutually distinguishing Navy type I to III piezo-ceramic materials are to be found in a document United States standard MIL-STD-1376 which is herein incorporated by reference.

5 Conveniently, the exciting means is operable to excite vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions. Operation at the modal resonance provides the advantage that vibration amplitude and associated stress levels in the transformer are magnified by a Q-factor of the resonance, thereby improving efficiency of the transformer compared to operation off-resonance.

10 Advantageously, the network is operable to phase shift and amplify the output signal to generate a drive signal for exciting and thereby sustaining vibrations within the transformer. Phase shifting and amplification provide a simple form of signal processing required for sustaining vibrations within the transformer. Preferably, the output signal is phase shifted in a range of  $30^\circ$  to  $150^\circ$  in  
15 the network to generate the drive signal.

It is desirable that the transformer should be capable of being driven to provide a high voltage magnification from the primary region to the secondary region. Thus, the exciting means advantageously incorporates amplifiers arranged in a bridge configuration operable to drive the  
20 transformer. The configuration enables the drive signal to have a peak-peak amplitude corresponding to up to twice a supply potential supplied to the amplifiers.

Advantageously, the exciting means incorporates at least one inductor through which the transformer is driven at its primary region, the inductor operable to electrically resonate with a  
25 capacitor provided by the primary region at a frequency corresponding to that of the vibrations. Incorporation of the inductor provides the advantages that:

- (a) the primary region is capable of being tuned to appear as a resistive load to the drive signal; and

- (b) higher harmonic components present in the drive signal can be attenuated, thereby counteracting spurious excitation of higher-order vibrational modes in the transformer and hence enhancing operating efficiency.

- 5 Conveniently, one of the inductors can incorporate a ferrite core. This enables the inductor to be compact.

- Conveniently, the circuit incorporates rectifying means for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in the form of a unipolar potential. Rectification provides the advantage of converting the output signal from the secondary region, namely an alternating signal, into a unipolar potential for output. Preferably, the rectifying means incorporates a rectifier diode operable to provide a conductive path for the output signal to a ground potential to assist with developing the unipolar output potential.
- 10

- 15 Advantageously, the transformer is operable to generate relatively high output potentials approaching 10 kV or more. To generate this potential, the transformer is operable to impart a greater voltage amplitude to the output signal relative to that of the drive signal.

- Preferably, the transformer is operable to vibrate in a longitudinal mode of acoustic resonance. Longitudinal modes of vibration can be symmetrical modes of resonance, thereby assisting to reduce vibrational energy loss from the transformer in comparison to unsymmetrical vibrational modes. Conveniently, the transformer is of elongate form operable to vibrate longitudinally along its elongate axis.
- 20

- 25 Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

30

In a second aspect of the invention, there is provided a method of operating a piezo-electric transformer, the method comprising the steps of:

- 5 (a) providing the transformer incorporating mutually vibrationally coupled primary and secondary regions, the secondary region providing an output signal from the transformer, the transformer being fabricated from a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz; and
- 10 (b) establishing a feedback network for processing the output signal to generate a drive signal and applying the drive signal to excite oscillatory vibrations in the primary region which couple to the secondary region, thereby generating the output signal in the secondary region and sustaining the vibrations in the transformer.

In a third aspect of the present invention, there is provided a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the primary region incorporating  
15 a stack of piezo-electric material elements, each element incorporating electrical connections for connecting a drive signal thereto and the secondary region incorporating electrical connections for extracting an output signal therefrom, characterised in that the piezo-electric transformer comprises a hard piezo-electric ceramic material having a dielectric loss of substantially 0.005 or less at 1  
20 kHz. Use of the hard piezo-electric material, for example a Navy type I or III piezo-ceramic material, improves efficiency of the transformer compared to an identical transformer fabricated using a softer piezo-electrical material, for example a Navy type II piezo-ceramic material.

Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive  
25 signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

Embodiments of the invention will now be described, by way of example only, with reference to  
30 the following diagrams in which:



Figure 1 is an illustration of a piezo-electric transformer according to the invention;

Figure 2 is a schematic of an electrical equivalent circuit to the transformer shown in Figure 1;

5 Figure 3 is a schematic diagram of a circuit according to the invention for operating the transformer in Figure 1; and

Figure 4 is a schematic diagram of an alternative circuit according to the invention for operating the transformer in Figure 1.

10

Referring now to Figure 1, there is shown a piezo-electric transformer according to the invention; the transformer is indicated by 10 and comprises a primary region indicated by 12 and a secondary region indicated by 14. The regions 12, 14 are both identical in size, namely 8 mm long (l), 6 mm wide (w) and 2 mm thick (t). Exposed faces of the regions 12, 14 are mutually parallel or orthogonal. Moreover, the regions 12, 14 are each mutually joined at an interface 16 where each region provides an abutting face of size 6 mm x 2 mm.

15

The secondary region 14 incorporates an end face 18 on an opposite side thereof to the interface 16. The face 18 is metallized with a vacuum-deposited or sprayed metallic film, for example a silver metallic film, to which an electrical connection S1 is made by wire bonding.

20

The primary region 12 comprises a stack of sixteen piezo-electric planar elements, for example an element 20, each slice having a thickness of 100  $\mu$ m and an area of 8 mm x 6 mm. When assembled, the stack is 2 mm thick to match the thickness (t) of the secondary region 14.

25

Moreover, each element is metallized on its major faces with a vacuum-deposited metallic film, for example a silver metallic film. The major faces of each element are electrically mutually isolated. The elements are electrically connected in parallel in the stack to which primary electrical connections P1, P2 are made by wire bonding to exposed major faces of an upper element 20a and a lower element 20b respectively of the primary region 12. The connections P1, P2 can alternatively be made to opposite side edges of the primary region 12 where metallic film connections on the major faces of the elements are accessible.

30

- The elements 20 and the secondary region 14 comprise a hard PZT piezo-electric ceramic material exhibiting a dielectric loss of 0.005 or less at a test frequency of 1 kHz. The hard material has a product reference PZT26 and is manufactured by a Danish company Ferroperm A/S, Hejreskovvej 18A, DK-3490 Kvistgaard, Denmark. The hard PZT26 material is to be contrasted with softer piezo-electric materials having product references PZT27 and PZT29 from the same company. The softer PZT27 and PZT29 materials exhibit reduced resonance Q-factors and greater dissipation when vibrating compared to the hard PZT26 material; moreover, such softer PZT materials exhibit a higher dielectric loss in the order of 0.02 at 1 kHz. Here, the dielectric loss of a piezo-electric material is defined as the tangent of the electrical loss angle observed when electrically driving the material. The dielectric loss also represents the ratio of resistance to reactance of a parallel equivalent circuit of a piezo-electric transformer made from the material. The dielectric loss can be measured directly using an impedance bridge, for example at an excitation frequency of 1 kHz.
- Table 1 contrasts material parameters associated with the hard PZT26 piezo-ceramic material with corresponding material parameters associated with the softer PZT27 and PZT 29 piezo-ceramic materials.

Table 1

Parameter	PZT26 (hard)	PZT27 (soft)	PZT29 (soft)
Relative dielectric constant @ 1 kHz	1300	1800	2900
Dielectric loss factor ( $\tan \delta$ )	0.003	0.017	0.019
Curie temperature ( $^{\circ}\text{C}$ )	330	350	235
Coupling factor $k_{33}$	0.68	0.7	0.75
Piezo-electric charge coefficient ( $10^{-12}$ C/N), $-d_{31}$	130	170	240
Density ( $10^3 \text{ kg/m}^3$ )	7.70	7.70	7.45
Resonant mechanical $Q_m$ factor	>1000	80	90

During manufacture, the elements and the secondary region 14 are poled prior to being joined together using a rigid epoxy bonding agent to fabricate the transformer 10. Poling involves

applying a momentary electric field to the region 14 and the elements of sufficient magnitude to cause a permanent electrical polarisation therein; the polarisation is reversible by heating to or above the Curie temperature in Table 1 or by applying a sufficiently powerful depolarising electric field.

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When assembled for operation, the transformer 10 can be mounted onto compliant air-filled expanded plastic foam. It can alternatively be supported on point mounts which engage onto areas of the transformer 10 corresponding to vibrational nodes when the transformer 10 is vibrating; such point mounts assist to enhance resonance Q-factor of the transformer 10 when resonating at one or more of its resonant modes by reducing vibrational energy loss therefrom. The use of foam plastics provides a robust shock-resilient mount for the transformer 10, thereby assisting to counteract fracture of the transformer 10 when subjected to high g-forces, for example accelerations in excess of 10g.

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Operation of the transformer 10 will now be described with reference to Figure 1. The connections P1, P2 are connected to a source (not shown in Figure 1) providing a drive signal which imposes an alternating drive potential difference between the connections P1, P2. Because the elements are polarised in a first direction parallel to an arrow 22, namely in a direction normal to major surfaces of the elements, the elements expand and contract in the first direction in response to the drive signal. This expansion and contraction of the elements in the first direction results in them exhibiting an associated lateral expansion and contraction in second and third directions indicated by arrows 24, 26 respectively. The arrows 22, 24, 26 are mutually perpendicular. On account of the primary and secondary regions 12, 14 being joined together and thereby vibrationally coupled together, the secondary region 14 vibrates in sympathy with the primary region 12. Since the secondary region 14 is polarised in a direction parallel to the arrow 26, acoustic vibrations in the secondary region 14 are capable of developing an alternating potential at the connection S1.

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The transformer 10 is capable of vibrating in a number of different resonance modes depending upon the frequency of the drive signal applied, each mode corresponding to a different manner in which the transformer 10 is capable of flexing. When the frequency of the drive signal corresponds to that of a particular mode, that particular mode becomes preferentially excited. The degree to

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which the mode is excited depends upon the magnitude of the drive signal and also on effectiveness of excitation of the mode from the connections P1, P2.

The transformer 10 is designed to function in a longitudinal mode of resonance at 100 kHz in which the regions 12, 14 alternately expand and contract in opposition in directions parallel to the arrow 26. This mode of operation results in there arising most motion at extremities of the regions 12, 14 remoter from the interface 16 and least motion at the interface 16; in other words, the interface 16 functions as a nodal point and exposed ends of the regions 12, 14 functional as antinodal points. When the secondary region 14 vibrates, stresses arising from periodic elongation thereof result in generation of an alternating potential at the connection S1. The transformer 10 is thereby capable of converting a relatively smaller drive potential applied to the primary region 12 between the connections P1, P2 into a corresponding relatively larger magnified potential at the connection S1. For example, a 5 volt peak-peak 100 kHz sinusoidal signal applied to the connections P1, P2 can result in generation of a 300 volt peak-peak sinusoidal signal at the connection S1. Signal magnification provided by the transformer 10 is referred as its magnification factor, N. The factor N is determined by physical dimensions of the transformer 10, namely its dimensions t and l, as well as its Q-factor associated with its longitudinal mode of resonance and also piezo-electric coupling coefficients associated with the primary and secondary regions 12, 14 respectively. Equation 1 expresses this relationship:

$$N = \frac{Q_m k_0 k_{13} k_{33} l}{t} \quad \text{Eq. 1}$$

where

$Q_m$  = resonant mechanical Q factor;

$k_0$  = proportionality coefficient;

$k_{13}$  = primary region coupling coefficient associated with coupling of piezoelectrically induced stress arising from applying an electric field in a primary region poling direction to stress in a direction perpendicular to the poling direction;

$k_{33}$  = secondary region coupling coefficient associated with coupling stress in the secondary region poling direction to a corresponding secondary electric field in the poling direction;

l = length of primary and secondary regions; and  
t = thickness of primary and secondary regions.

Incorporation of a plurality of planar elements into the primary region 12 increases current output performance of the transformer 10 compared to a piezo-electric transformer of similar external physical dimensions and material incorporating only a single element in its primary region.

Referring now to Figure 2, there is shown an electrical equivalent circuit to the transformer 10, the circuit being indicated by 100. Components in the circuit 100 do not exist in reality but represent mechanical resonance characteristics of the primary and secondary regions 12, 14 near their 100 kHz longitudinal resonance mode.

The primary region 12 includes the connections P1, P2 which are mutually connected through a series resonant circuit comprising an inductor  $L_p$ , a capacitor  $C_p$  and a resistor  $R_p$ ; the series resonant circuit is resonant at a frequency  $f_p$ . Moreover, the connections P1, P2 are also mutually connected through two capacitors  $C_{ep}$  connected in series. The capacitors  $C_{ep}$  represent an electrical capacitance between metallisation layers incorporated onto the slices in the primary region 12 and are each in the order of several hundred nanofarads. The series resonant circuit represents mechanical resonance of the primary region 12 when vibrating in its longitudinal mode of vibration.

The secondary region 14 includes a parallel resonant circuit comprising a resistor  $R_s$ , an inductor  $L_s$  and a capacitor  $C_s$  connected in parallel with a current source  $I_s$ . The parallel resonant circuit is resonant at a frequency  $f_s$ . The current source  $I_s$  incorporates two terminals, namely:

- (a) a first terminal connected to one side of the parallel resonant circuit and also to a junction where the capacitors  $C_{ep}$  mutually join; and
- (b) a second terminal connected to another side of the parallel resonant circuit and also to the connection S1.

In operation, most power is delivered to the primary region 12 when a drive signal applied across the connections P1, P2 is a sinusoidal signal having a frequency equal to  $f_p$ . When the series resonant circuit is driven at resonance, it presents a resistive load  $R_p$  across the connections P1, P2. However, the capacitors  $C_p$  appear in parallel with  $R_p$  and provide a capacitive load to the connections P1, P2; as a consequence, a primary current  $i_p$  supplied to the connections P1, P2 is phase advanced relative to a potential developed across the connections P1, P2 at the frequency  $f_p$ . The inventors have appreciated that determination of current-voltage phase difference when driving the primary region 12 is not an optimal manner in which to ensure that the transformer 10 is operating efficiently at resonance because it is difficult to determine precisely when the series resonant circuit is being driven at its resonant frequency  $f_p$ .

In operation, the parallel resonant circuit in the secondary region 14 exhibits a slightly different resonant frequency relative to the series resonant circuit in the primary region 12; this corresponds to  $f_p$  and  $f_s$  being unequal, namely there arises a frequency difference  $\Delta f$  equal to  $f_s - f_p$ . This frequency difference varies depending upon load applied to the terminal S1. Thus, the inventors have appreciated that operating the primary region 12 at its resonant frequency  $f_p$  does not necessarily ensure that the secondary region 14 is being operated precisely at its resonance. In consequence, it is found that efficiency of operation of the transformer 10 reduces considerably when a load is applied to the connection S1.

When resonating in its longitudinal mode at 100 kHz and unloaded, the transformer 10 exhibits a resonance Q-factor of approximately 300. When loaded at the connection S1, this Q-factor can reduce to 60 which modifies  $\Delta f$ . Mechanisms for acoustic energy loss from the transformer 10 which determine its Q-factor include:

- (a) intrinsic losses within the PZT material arising from frictional losses at PZT particle grain boundaries therein;
- (b) air damping effects;
- (c) acoustic losses to a foam or point mount employed to support the transformer 10; and
- (d) electrical load applied to the connection S1 which absorbs acoustic energy from the secondary region 14.

In operation, mechanism (d) is most significant at changing the Q-factor and hence  $\Delta f$ .

5 The inventors have appreciated that driving the transformer 10 closer to its optimum operating condition is a complex problem. Whereas fixed frequency primary drive is conventionally employed in piezo-electric transformer power supplies, the inventors have realised that output from the secondary connection S1 provides a most reliable signal from which to derive a drive signal for the primary region 12 which enables the transformer 10 to operate more efficiently when loaded at its secondary region 14.

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Referring now to Figure 3, there is shown a schematic diagram of a circuit according to the invention for operating the transformer 10. The circuit is indicated by 200 and comprises:

- (a) the piezo-electric transformer 10;
- 15 (b) a bias network indicated by 210 and included within a dotted line 220;
- (c) first and second amplifiers indicated by 230, 250 and included within dotted lines 240, 260 respectively;
- (d) a feedback network indicated by 270 and included within a dotted line 280; and
- (e) an output network indicated by 290 and included within a dotted line 300.

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The circuit 200 is connected to supply lines Vs and 0v which are operable to provide input power to the circuit 200.

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The bias network 210 incorporates two 100k resistors R1, R2 connected in series, namely the resistors R1, R2 are each connected at one end thereof to the supply lines Vs, 0v respectively. The resistors R1, R2 are operable to provide a bias potential where they are mutually connected.

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The amplifiers 230, 250 are identical and each incorporates an operational amplifier connected to the supply lines Vs, 0v. The operational amplifiers are arranged in inverting configuration with resistors R3, R4 defining a voltage gain provided by the first amplifier 230 and resistors R5, R6 defining a voltage gain provided by the second amplifier 250. The resistors R3, R6 are 470k

resistors and the resistors R4, R5 are 3M3 resistors. The bias network 210 is connected to the amplifiers 230, 250 and operable to provide a bias potential thereto. Outputs from the amplifiers 230, 250 are connected to connections P1, P2 of the transformer 10 respectively. The amplifier 230 incorporates an input which is connected to an output from the feedback network 270, and the  
5 amplifier 250 incorporates an input which is connected to the output from the amplifier 230.

The feedback network 270 comprises a 2M2 resistor R7 and a 10 pF capacitor C1 connected in series to the supply line 0v. The resistor R7 provides a input which is connected to the connection S1 of the transformer 10. A junction where the resistor R7 is joined to the capacitor C1 provides  
10 a output which is connected to the input of the amplifier 230 through a 100 nF coupling capacitor C3.

The output network 290 comprises two silicon rectifier diodes D1, D2 exhibiting a reverse breakdown voltage of approximately 1kV and a fast switching speed of 100 ns or less. The diode  
15 D1 is connected by its cathode to the connection S1 and its anode to the supply line 0v. Moreover, the diode D2 is connected by its anode to the connection S1 and its cathode to a secondary output S2 from the circuit 200. Furthermore, the network 290 also incorporates a 100nF output capacitor C2 connected between the output S2 and the 0v supply line. In operation, a high voltage potential of several hundred volts relative to the supply line 0v is provided at the output S2. The diode D1  
20 is arranged to provide a discharge path to the supply line 0v to assist with developing the high potential at the output S2.

The feedback network 270 is arranged to exhibit a time constant which is at least five times longer than a cycle time period associated with the frequency  $f_s$ . This ensures that a signal provided by  
25 the network 270 to the amplifier 230 is approximately in a range of 30° to 90° phase shifted relative to an output signal provided by the transformer 10 at the connection S2; the phase shift is necessary for the circuit 200 to maintain oscillation. However, the circuit 200 is capable of oscillating satisfactorily for a phase shift in a range of 30° to 150° in the network 270; extra components are required in the network 270 to obtain phase shifts in excess of 90°.



Operation of the circuit 200 will now be described with reference to Figure 3. When power is supplied through the supply lines Vs, 0v to the circuit 200, the bias network 210 provides a bias potential to the amplifiers 230, 250, the bias potential substantially intermediate between Vs and 0v. The bias potential biases the amplifiers 230, 250 to operate symmetrically with reference to the bias potential.

The amplifiers 230, 250 provide voltage gain around a feedback loop comprising the transformer 10, the feedback network 270 and the amplifiers 230, 250. The feedback loop is arranged to have greater than unity gain therearound at the frequency fs, namely at approximately 100 kHz; the feedback network 270 provides a phase shift required for sustaining oscillation around the loop. When the circuit 200 is initially energised, noise injected into the circuit 200 by the amplifiers 230, 250 becomes amplified around the feedback loop to establish a major oscillation at the frequency fs. This feedback loop provides the advantage that the circuit 200 will automatically restart in the event of its supply lines being momentarily interrupted or the transformer 10 being subjected to violent shock which disturbs its vibration.

As illustrated in Figure 2, the secondary connection S1 is capacitively coupled within the transformer 10 to the primary connections P1, P2. As a consequence, the diode D1 provides a discharge path for the connection S1 during a first half cycle and the diode D2 provides a charging path to charge the capacitor C2 during a second half cycle. The capacitor C2 thereby becomes progressively charged in operation to a high potential of several hundred volts. The high potential is a unipolar potential.

The circuit 200 incorporates an important feature that the primary connections P1, P2 are driven by a signal derived from the secondary connection S1. This feature enables the circuit 200 to adapt to changes in the secondary region 14 resonant frequency fs in response to loading applied to the output S2, thereby enhancing efficiency of the circuit 200 under load conditions.

The amplifiers 230, 250 are connected in bridge configuration. This configuration provides the advantage that the amplifiers 230, 250 are capable of driving the transformer 10 with a drive signal across its primary connections P1, P2 which has a peak-peak voltage amplitude of approximately

twice that of a potential difference between the supply lines Vs, 0v. Thus, this configuration makes the circuit 200 capable of providing a high output voltage approaching several hundred volts when operating on a supply line potential difference of 5 volts.

- 5 It is important that the diodes D1, D2 are capable of switching sufficiently rapidly to counteract the diodes D1, D2 momentarily both conducting and thereby shorting the capacitor C2 to the supply line 0v; if the diodes D1, D2 switch insufficiently rapidly, operating efficiency of the circuit 200 is degraded. Small junction area silicon diodes incorporating graded doped junctions to give high inverse breakdown voltage characteristics are especially suitable for use as the diodes D1, D2.

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Although the circuit 200 is arranged to excite the transformer 10 therein to vibrate in its longitudinal mode at resonance at a frequency of 100 kHz, the circuit 200 can be adapted to operate at a higher resonance mode of the transformer 10, or example at 200 kHz; to achieve operation at such a higher-order mode, the feedback network 270 can incorporate a bandpass filter adapted to preferentially transmit signals in a frequency range of the higher-order mode, thereby enabling the feedback loop to maintain oscillation in the frequency range of the higher order mode and not at lower order modes. Such higher frequency operation provides the advantage that less ripple is evident at the output S2 although the diodes D1, D2 need to be capable of switching more rapidly in order to counteract increased switching losses occurring as a consequence of operating at higher frequencies.

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Referring now to Figure 4, there is shown a schematic diagram of an alternative circuit according to the invention for operating the transformer 10. The alternative circuit is indicated by 400 and is identical to the circuit 200 except that an inductor L1 is incorporated between the output of the amplifier 250 and the connection P2 of the transformer 10. The inductor L1 is arranged to exhibit an inductance which is resonant at the frequency fs with the series connected capacitors Cep shown in Figure 2.

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Incorporation of the inductor L1 provides the advantages that:

- (a) the primary region can be tuned so that longitudinal resonance thereof corresponds to the current  $i_p$  and a drive potential applied across the connections P1, P2 being mutually in phase; and
- (b) inclusion of the inductor L1 assists to prevent square-wave drive signals provided by the amplifiers 230, 250 from spuriously exciting higher-order resonance modes in the transformer 10 when attempting to drive it at its fundamental longitudinal vibrational mode. Spurious oscillation can arise when the drive signal is a square wave signal including an extensive spectrum of odd harmonics whose associated frequencies can coincide with frequencies of higher order resonant modes of the transformer 10.

The inductor L1 can be fabricated by winding enameled copper wire around a small ferrite bead to provide an inductance in the order of 30  $\mu$ H to resonate at 100kHz with the capacitors Cep. Use of a ferrite bead provides a compact miniature inductor assembly. Alternatively, the inductor L1 can be fabricated as an air-cored coil; such construction is more attractive for higher power applications. Moreover, if required, the inductor L1 can comprise a plurality of smaller inductors connected together.

Experimental verification has demonstrated that inclusion of the inductor L1 improves operating efficiency of the circuit 400 compared to the circuit 200.

In a modified version of the circuit 400, an additional inductor is incorporated between the connection S1 and the networks 270, 290; inclusion of this inductor further enables fine tuning of the transformer 10 to be achieved. The additional inductor is arranged to resonate with a capacitance provided by the transformer 10 at its connection S1 at a frequency corresponding to that of a operational mechanical resonance of the transformer 10. Moreover, in a further modified version of the circuit 400, there can be incorporated the additional inductor connected to the connection S1 as described above with the inductor L1 omitted.

It will be appreciated by those skilled in the art that modifications to the transformer 10 and to the circuits 200, 400 can be made without departing from the scope of the invention. For example, the transformer 10 can incorporate in a range of 2 to 40 elements. Moreover, physical dimensions of

the transformer 10 can be modified, for example it can be made smaller to operate at a relatively higher frequency, or it can be made longer and thinner to provide it with an enhanced magnification factor  $N$ . The enhanced magnification factor is desirable when greater output potentials are to be generated.

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With regard to construction of the transformer 10, its elements can be assembled by eutectic metal bonding techniques instead of employing rigid epoxy agents; such techniques provide a higher  $Q$ -factor to a transformer thereby fabricated. Moreover, the transformer 10 can be adapted to incorporate one primary region and two secondary regions bonded onto opposing side faces of the primary region, this provides the advantage that greater secondary region output currents can be thereby obtained.

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Although hard PZT materials are used for fabricating the transformer 10, alternative hard man-made piezoelectric materials can be substituted if necessary, for example materials incorporating piezo-electric polyvinylidene fluoride (PVDF).

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The transformer 10 and its associated circuits 200, 400 are capable of providing high potentials suitable for operating high voltage sensors, for example miniature Geiger-Muller tubes for detecting ionising radiation, as well as assisting to provide rear illumination in back-lit liquid crystal displays. Since the transformer 10 and its circuits 200, 400 are capable of being compact, they can be incorporated into personnel-wearable equipment, for example portable electronic radiation dose monitors including solid state memory for data recordal purposes.

## CLAIMS

1. A piezo-electric transformer circuit (200) incorporating a piezo-electric transformer (10) comprising mutually vibrationally coupled primary and secondary regions (12, 14), the secondary region (14) operable to provide an output signal for use in generating an output from the circuit (200), and vibration exciting means (210, 230, 250, 270) for exciting the transformer (10) into vibration to generate the output signal, characterised in that the transformer (10) comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz frequency.
2. A circuit according to Claim 1 wherein the exciting means (210, 230, 250, 270) is operable to excite vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions.
3. A circuit according to Claim 1 or 2 wherein the exciting means incorporates a network (270) operable to phase shift and amplify the output signal to generate a drive signal for exciting and thereby sustaining vibrations within the transformer (10).
4. A circuit according to Claim 3 wherein the network (270) is operable to phase shift the output signal in a range of  $30^{\circ}$  to  $150^{\circ}$  to generate the drive signal.
5. A circuit according to Claim 3 wherein the network (270) is operable to phase shift the output signal in a range of  $30^{\circ}$  to  $90^{\circ}$  to generate the drive signal.
6. A circuit according to any one of Claims 1 to 5 wherein the exciting means incorporates amplifiers (230, 250) arranged in a bridge configuration operable to drive the transformer (10).
7. A circuit according to any one of Claims 1 to 6 wherein the exciting means (210, 230, 250, 270) incorporates at least one inductor through which the transformer (10) is driven at its

primary region (12), the inductor operable to electrically resonate with a capacitor provided by the primary region (12) at a frequency corresponding to that of the vibrations.

8. A circuit according to Claim 7 wherein said at least one inductor incorporates a ferrite core.
9. A circuit according to any preceding claim incorporating rectifying means (290) for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in the form of a unipolar output potential.
10. A circuit according to Claim 9 wherein the rectifying means(290) incorporates a rectifier diode (D1) operable to provide a conductive path for the output signal to a ground potential to assist with developing the unipolar output potential.
11. A circuit according to any preceding claim wherein the transformer (10) is operable to impart a greater voltage amplitude to the output signal relative to that of the drive signal.
12. A circuit according to any preceding claim wherein the transformer (10) is operable to vibrate in a longitudinal mode of acoustic resonance.
13. A circuit according to any preceding claim wherein the primary region (12) of the transformer (10) comprises a stack of mutually joined piezo-electric material elements (20), each element (20) incorporating electrical connections and arranged to be excited in parallel with other of the elements (20).
14. A circuit according to Claim 13 wherein the transformer (10) incorporates in a range of 2 to 40 elements in the primary region (12) and a single element in the secondary region (14).
15. A method of operating a piezo-electric transformer (10), the method comprising the steps of:

- (a) providing the transformer (10) incorporating mutually vibrationally coupled primary (12) and secondary (14) regions, the secondary region (14) providing an output signal from the transformer (10), the transformer (10) being fabricated from a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz; and
- (b) establishing a feedback network (210, 230, 250, 270) for processing the output signal to generate a drive signal and applying the drive signal to excite oscillatory vibrations in the primary region (12) which couple to the secondary region (14), thereby generating the output signal in the secondary region and sustaining the vibrations in the transformer.
16. A method according to Claim 15 wherein the vibrations are at a frequency corresponding to a modal resonance of the primary and secondary regions (12, 14).
17. A method according to Claim 15 or 16 wherein the output signal is phase shifted and amplified in the network (210, 230, 250, 270) to generate the drive signal.
18. A method according to Claim 17 wherein the output signal is phase shifted in a range of  $30^{\circ}$  to  $150^{\circ}$  in the network (270) to generate the drive signal.
19. A method according to Claim 15, 16, 17 or 18 wherein the transformer (10) is driven from amplifiers (230, 250) arranged in a bridge configuration.
20. A method according to any one of Claims 15 to 19 wherein the transformer (10) is driven at its primary region (12) through at least one inductor arranged to electrically resonate with a capacitor provided by the primary region (12) at a frequency corresponding to that of the vibrations.
21. A method according to Claim 20 wherein said at least one inductor incorporates a ferrite core.
22. A method according to Claim 20 or 21 wherein signals from the secondary region (14) of the transformer (10) are extracted through an inductor arranged to electrically resonate

with a capacitance provided by the secondary region (14) at a frequency corresponding to that of the vibrations.

23. A method according to any one of Claims 15 to 22 wherein the output signal is rectified to provide a unipolar output potential (S2) from the transformer (10).
24. A method according to Claim 23 wherein the output signal is directed through a rectifier diode (D1) to a ground potential, the diode (D1) operative to provide a conductive path to assist with developing the unipolar output potential.
25. A method according to any one of Claims 15 to 24 wherein the transformer (10) is of elongate form operable to vibrate longitudinally along its elongate axis.
26. A method according to any one of Claims 15 to 25 wherein the transformer (10) is operable to impart a greater voltage amplitude to the output signal relative to the drive signal.
27. A method according to one of Claims 15 to 26 wherein the transformer (10) is operable to vibrate in a longitudinal mode of mechanical resonance.
28. A method according to any one of Claims 15 to 27 wherein the primary region (12) comprises a stack of mutually joined piezo-electric material elements (20), each element (20) incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements.
29. A method according to Claim 28 wherein the transformer (10) incorporates in a range of 2 to 40 elements in the primary region (12) and a single element in the secondary region (14).



30. A personnel-wearable sensing apparatus operable according to a method claimed in any one or more of Claims 15 to 19 for generating an elevated bias potential for use in the apparatus.
31. A piezo-electric transformer (10) comprising mutually vibrationally coupled primary (12) and secondary regions (14), the primary region (12) incorporating a stack of piezo-electric material elements (20), each element (20) incorporating electrical connections for connecting a drive signal thereto and the secondary region (14) incorporating electrical connections for extracting an output signal therefrom, characterised in that the transformer (10) comprises a piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz.
32. A transformer according to Claim 30 or 31 wherein the transformer (10) incorporates in a range of 2 to 40 elements in the primary region (12), and a single element in the secondary region (14).
33. A personnel-wearable sensing apparatus incorporating a transformer (10) according to any one of Claims 31 to 32, the transformer (10) operable to generate a bias potential for use in the apparatus.

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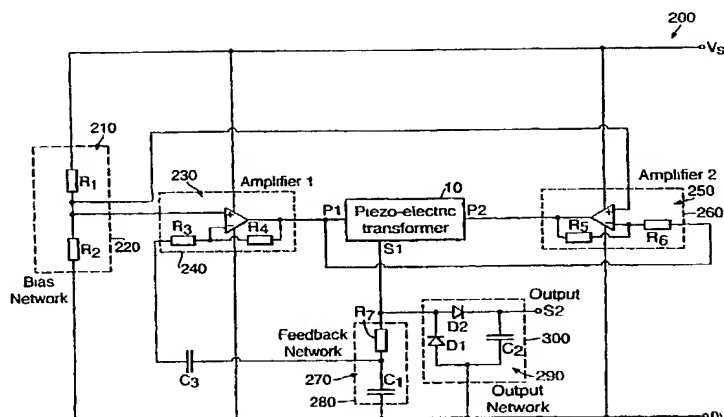
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## (54) Title: PIEZO-ELECTRIC TRANSFORMER CIRCUIT



(57) Abstract: The invention relates to a piezo-electric transformer circuit (200) incorporating a piezo-electric transformer (10) comprising a multi-element primary region (12) and a single element secondary region (14) mutually joined together. In operation, the circuit (200) applies a drive signal to the primary region (12) to excite the primary and secondary regions (12, 14) into longitudinal resonance, thereby generating a high potential signal at the secondary region (14). The drive signal is derived from the signal at the secondary region (14) in a self oscillating feedback loop configuration. The transformer (10) is fabricated from a hard piezo-electric ceramic material having a dielectric loss of substantially 0.005 or less at 1 kHz. Although such a hard ceramic does not provide as high a charge coefficient as softer piezo-electric ceramic materials, it is found that hard ceramics provide surprisingly improved energy conversion when used in piezo-electric transformer power supplies.

**Fig. 1.**

A perspective view of a rectangular frame assembly 10. The assembly includes a primary member 12 and a secondary member 18. The primary member 12 has a top edge 14 and a bottom edge 16. The secondary member 18 is positioned above the primary member 12. The assembly is shown in a perspective view with dimensions L (length) and W (width). A cross-sectional view at the right end shows the thickness t of the members. A coordinate system with axes 22, 24, and 26 is indicated.

Fig.2.

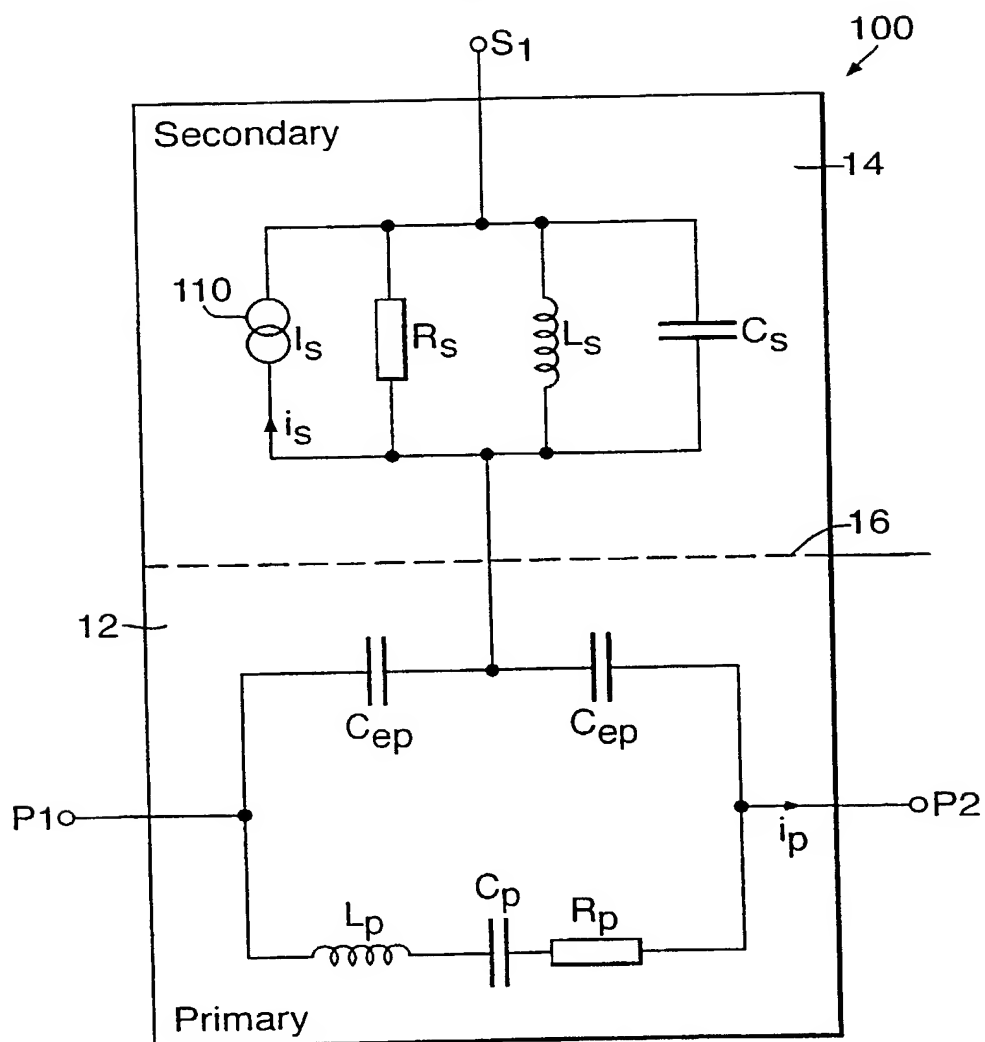
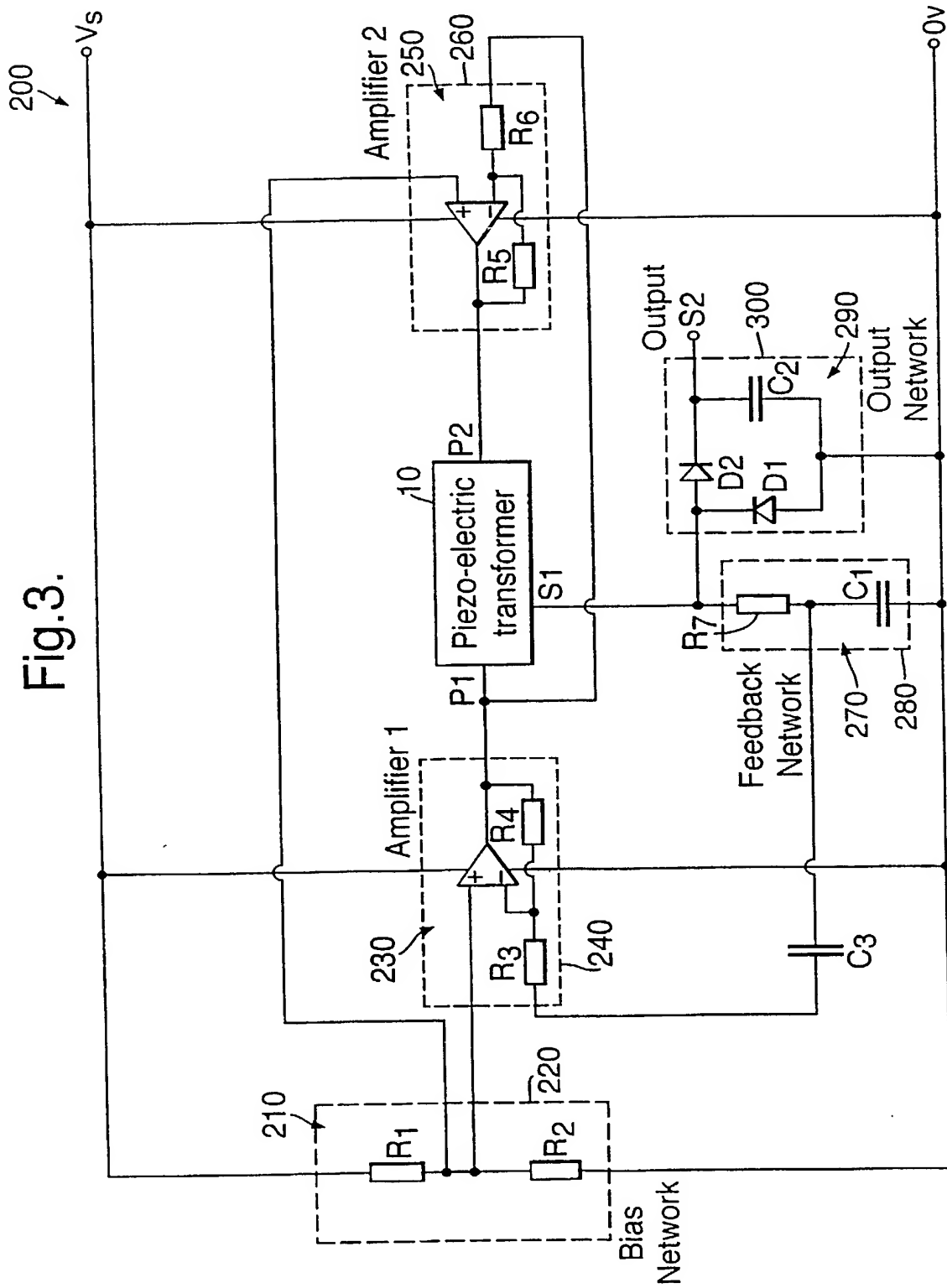
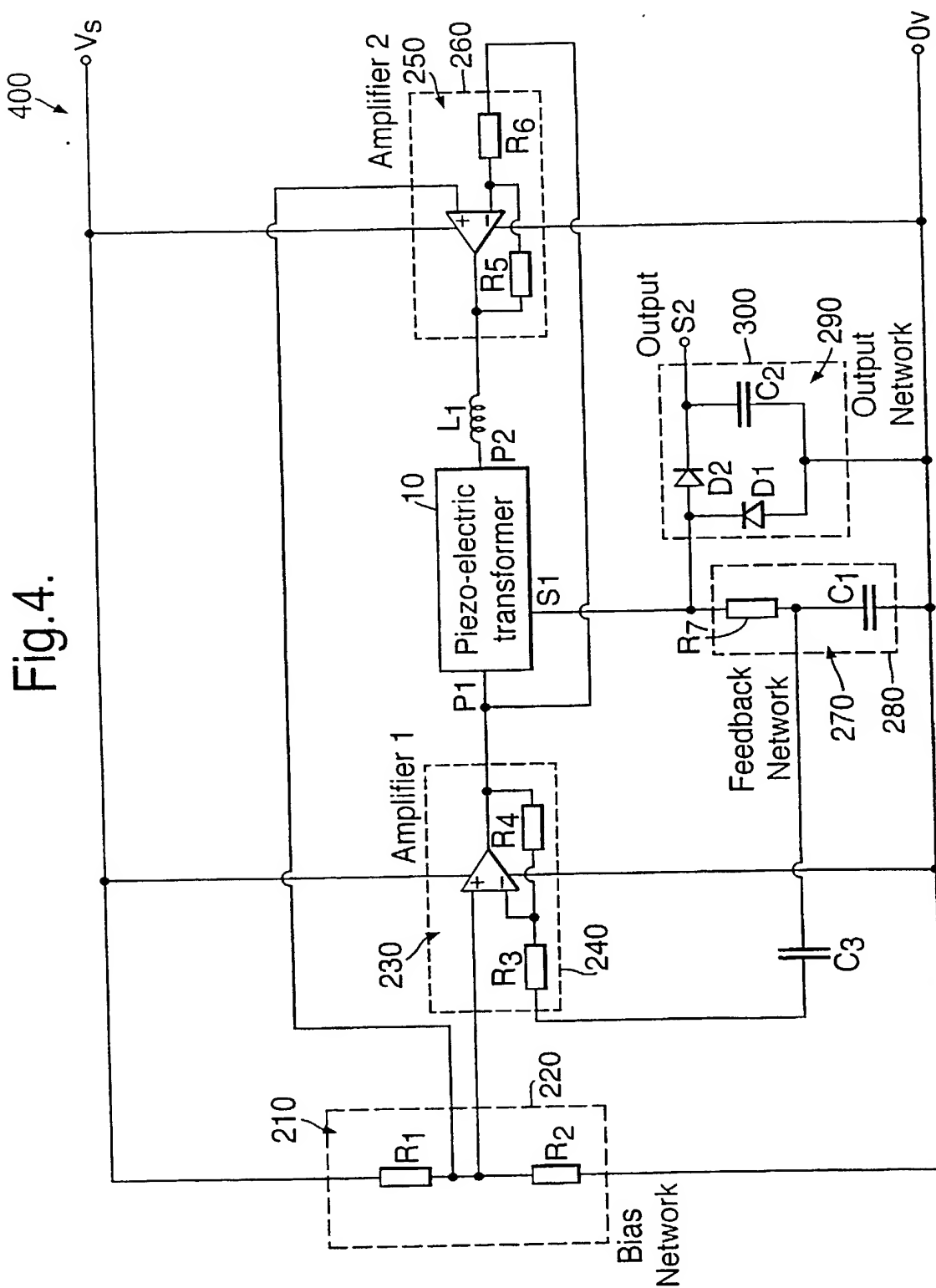


Fig.3.





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Examiner Name

As a below named inventor, I hereby declare that:

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

PIEZO-ELECTRIC TRANSFORMER CIRCUIT

(Title of the Invention)

the specification of which

☐ is attached hereto  
OR

☒ was filed on (MM/DD/YYYY)

DECEMBER 20, 2001

as United States Application Number or PCT International

Application Number

10/019,141

and was amended on (MM/DD/YYYY)

(if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37 Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code §119 (a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365 (a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YYYY)	Priority Not Claimed	Certified Copy Attached?	
				YES	NO
9914516.1	United Kingdom	06.23.99	<input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input checked="" type="checkbox"/>

☐ Additional foreign application numbers are listed on a supplemental priority sheet attached hereto:

I hereby claim the benefit under Title 35, United States Code § 119(e) of any United States provisional application(s) listed below.

Application Number(s)	Filing Date (MM/DD/YYYY)	<input type="checkbox"/> Additional provisional application numbers are listed on a supplemental priority sheet attached hereto.

Burden Hour Statement: This form is estimated to take .4 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington, DC 20231.

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## DECLARATION

Page 2

I hereby claim the benefit under Title 35, United States Code §120 of any United States application(s), or §365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT international application in the manner provided by the first paragraph of Title 35, United States Code §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations §1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. Parent Application Number	PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number (if applicable)

☐ Additional U.S. or PCT international application numbers are listed on a supplemental priority sheet attached hereto.

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

☐ Firm Name  Customer Number  or label   
☒ OR  
☒ List attorney(s) and/or agent(s) name and registration number below:

Name	Registration Number	Name	Registration Number
David B. Kirschstein, Esq.	17,244		
Alan Israel, Esq.	27,564		
Martin W. Schiffmiller, Esq.	30,421		

☐ Additional attorney(s) and/or agent(s) named on a supplemental sheet attached hereto.

Please direct all correspondence to: ☐ Customer Number  or label  OR ☒ Fill in correspondence address below

Name KIRSCHSTEIN, OTTINGER, ISRAEL & SCHIFFMILLER, P.C.  
 Address 489 Fifth Avenue  
 Address   
 City New York State New York ZIP 10017-6105  
 Country United States Telephone (212) 697-3750 Fax (212) 949-1690

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Name of Sole or First Inventor: ☐ A petition has been filed for this unsigned inventor

Given Name Anthony Middle Initial J Family Name SALLOWAY Suffix e.g. Jr.

Inventor's Signature X AS Salloway Date X 21/01/02

Residence: City Northampton State  Country United Kingdom Citizenship British

Post Office Address 50 Booth Lane S, Northampton, NN3 3EP, (GB) UK

Post Office Address

City Northampton State  Zip NN3 3EP Country United Kingdom Applicant Authority

☒ Additional inventors are being named on supplemental sheet(s) attached hereto



10019141 050302



Type a plus sign (+) inside this box → ☐

# DECLARATION

## ADDITIONAL INVENTOR(S) Supplemental Sheet

20

Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name	Caroline	Middle Initial	E	Family Name	MILLAR	Suffix	
Inventor's Signature	K C E millar				Date	X 28/01/02	
Residence: City	Nether Hayford, Northamptonshire	State		Country	United Kingdom	Citizenship	British
Post Office Address	Glenmore, 20 Linsesh Wood Close, Bramley, GU5 0EG, (GB)UK						
Post Office Address							
City	Nether Hayford, Northamptonshire	State		Zip	NN7 3NH	Country	United Kingdom
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature					Date		
Residence: City		State		Country		Citizenship	
Post Office Address							
Post Office Address							
City		State		Zip		Country	
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature					Date		
Residence: City		State		Country		Citizenship	
Post Office Address							
Post Office Address							
City		State		Zip		Country	
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature					Date		
Residence: City		State		Country		Citizenship	
Post Office Address							
Post Office Address							
City		State		Zip		Country	
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature					Date		
Residence: City		State		Country		Citizenship	
Post Office Address							
Post Office Address							
City		State		Zip		Country	

☐ Additional inventors are being named on supplemental sheet(s) attached hereto